PERGAMON

Energy Conversion & Management 41 (2000) 493–504

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

Application of Superconducting Magnetic Energy Storage unit in multi-machine power systems

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Received 14 October 1998; accepted 16 May 1999

Abstract

The use of Superconducting Magnetic Energy Storage (SMES) units to improve the dynamic stability of a multi-machine power system is investigated. The SMES unit is equipped with two independent controllers which ensures the effective management of its active and reactive power capabilities. The parameters of these controllers are determined once off-line. The simulation results show that the SMES unit is able to restore system stability even for disturbances of large magnitude. The control algorithms for SMES unit are simple and implementation will require very little hardware.

Keywords: Energy storage; Multi-machine power system; Dynamic stability; Control

1. Introduction

The use of Superconducting Magnetic Energy Storage (SMES) is considered to be an effective measure for suppressing system instabilities of electrical power systems because of the following reasons:

1. Since it is a fast acting device, power transfer can be done within a fraction of a second.
2. It can be sited at strategic locations for maximum benefit.
3. It can be used for control of both active and reactive powers.
4. The power loss in the superconductor coil is very low.

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0196-8904/00/$ - see front matter
PII: S0196-8904(99)00100-4

Owing to the substantial development in high temperature superconducting material technology, application of superconductors has become a relevant issue in electrical engineering [1]. Since the successful commissioning test of a 30 MJ SMES unit at the Bonneville Power Administration (BPA) substation in Tacoma, WA, a new chapter has opened for bulk energy storage. Also, researchers have found that the energy stored in such units can be used for many purposes in addition to load levelling. The SMES unit is designed to store electric energy in its superconducting magnetic coil. Controlling the firing angle of the converters feeding the unit changes the amount of energy supplied to (or received by) the SMES unit. This energy can be supplied to the power system as and when it is needed by appropriate control of the SMES unit. Several articles have reported the use of SMES units for load frequency stabilization and automatic generation control [2–8].

References [3–5] investigate the use of SMES in two-area power systems. All generating units in a given area have been modelled by a single equivalent unit. The model used in the analysis is valid only for small disturbances around a given operating point. The basic concepts, circuit requirements and terminal characteristics of a SMES unit are well presented in Ref. [3]. Although the turbine and boiler dynamics are modelled rigorously in this work, an oversimplified model is used to represent the synchronous machine. In all these references, only the real power flow of the SMES has been considered. In Ref. [6], control of the reactive power of the SMES has been included, but the analysis is limited to a single machine system. References [2,7,8] deal with a single synchronous machine connected to an infinite bus bar over a transmission line. The system equations have been linearised, and in Ref. [7], the controllers are designed to improve damping of the system oscillations.

An infinite bus bar represents a large power system with constant voltage and constant frequency. It is assumed that whatever happens with the loads or generators within the infinite

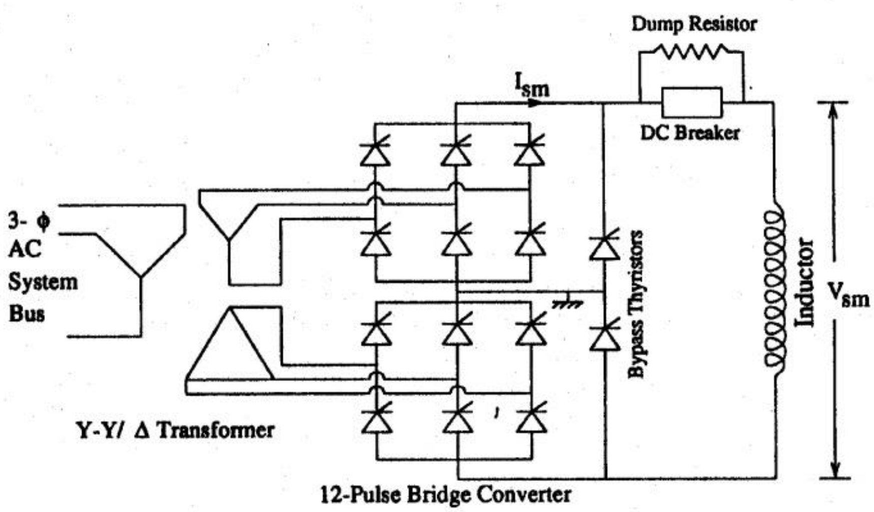

Fig. 1. The schematic diagram of the SMES unit.

bus bar does not affect the rest of the system. While these are valid assumptions for large systems with strong interconnections, they do not hold true in the case of small and isolated power systems. In such cases, a disturbance occurring anywhere affects the entire power system, and therefore, the performance of the entire power system has to be investigated.

In this paper, a SMES unit is used in a multi-machine power system with simultaneous control of the active and reactive powers. The controller structure is very simple. The gains of the PI controller are determined by the pole assignment technique based on modal control theory [9]. The gain of the voltage controller is determined by simulating a large disturbance. The machine, the lines and the SMES units in the power system are modelled accurately. To show the effectiveness of the SMES unit, simulation studies are done by considering disturbances in one of the interconnected lines. The results are presented and discussed.

2. SMES unit modelling

The SMES unit consists of a d.c. superconducting inductor, a 12-pulse Graetz bridge converter and a Y–Y and Y–Δ connected transformer as shown in Fig. 1. A helium refrigerator and a Dewar system, which encloses the inductor, are used to keep the temperature of the inductor well below the critical temperature of the superconductor. The transformers are needed to convert the high voltage and low current of the power system to the low voltage and high current required by the SMES. The transformers are connected in series on the secondary sides through the bridge converter, while they are connected in parallel on the primary sides to the three-phase a.c. bus bar.

The d.c. output voltage V_{smi} of each bridge can be controlled by controlling the firing angle α_i of that bridge. When Gate Turn-Off thyristors (GTOs) are used in place of ordinary thyristors in the two bridges, forced commutation is possible, and V_{smi} changes according to the relationship

$$V_{smi} = V_{sm0} \cos \alpha_i \tag{1}$$

$$V_{sm0} = \frac{3\sqrt{6}V}{\pi}$$

where V is the output phase rms voltage, α is the delay angle, V_{smi} is the per unit bridge voltage of the bridge no. i and V_{sm0} is the no load per unit bridge voltage.

Since the two bridges are in series, the total voltage across the inductor is

$$V_{sm} = V_{sm1} + V_{sm2} = V_{sm0}(\cos \alpha_1 + \cos \alpha_2). \tag{2}$$

The superconducting inductor is very close to being an ideal load, and the applied voltage V_{sm} charges the inductor according to the relationship

$$L_{sm}\frac{dI_{sm}}{dt} = V_{sm} \tag{3}$$

or

$$I_{sm} = I_{sm0} + \frac{1}{L_{sm}} \int_{t_0}^{t} V_{sm}(\tau)\mathrm{d}\tau \tag{4}$$

where I_{sm} is the d.c. current in the superconducting inductor. The real power flow into the conductor through each bridge is

$$P_{smi} = V_{smi} I_{sm} = V_{sm0} I_{sm} \cos \alpha_i \tag{5}$$

and the reactive power flow is

$$Q_{smi} = V_{sm0} I_{sm} \sin \alpha_i. \tag{6}$$

Therefore, the total three phase real and reactive power flows into the SMES are

$$P_{sm} = V_{sm0} I_{sm}(\cos \alpha_1 + \cos \alpha_2) \tag{7}$$

$$Q_{sm} = V_{sm0} I_{sm}(\sin \alpha_1 + \sin \alpha_2). \tag{8}$$

For 'charging' the SMES unit at the maximum rate, V_{sm} should be held at its maximum value, corresponding to rectifier operation with $\alpha = 0$. The current the increases nearly as a linear function of time until the base current $I_{sm} = 1.0$ p.u. is reached. Then, α must be adjusted so that the current is held constant. From Eq. (1), this corresponds to $\alpha = 90°$ for normal operating conditions. At any time during the charging period, the stored energy is

$$W_L = \frac{1}{2} L_{sm} I_{sm}^2 \quad \text{p.u.} \tag{9}$$

With constant V_{sm}, the inductor current I_{sm} can be expressed as

$$I_{sm} = \frac{V_{sm}}{L_{sm}} t \quad \text{p.u.} \tag{10}$$

While 'discharging', the inductor current should not be allowed to reach zero to prevent the possibility of discontinuous conduction. To avoid this, the lower limit of the inductor current is set at 30% of I_{sm0} [7]. Also, it is desirable to set the rated inductor current I_{sm0} such that the maximum allowable energy absorption equals the maximum allowable energy discharged. This makes SMES unit equally effective in damping swings caused by a sudden increase as well as a decrease in the load. Thus, if the lower limit of inductor current is chosen at 0.3 I_{sm0}, the upper limit, based on equal energy absorption/discharge, becomes 1.38 I_{sm0}. When the inductor current reaches either of these limits, the dependence of P_{sm} on speed deviation is discontinued, until the speed deviation swings to the other side.

Furthermore, due to the constraints of hardware implementation of the voltage and current ratings of GTO thyristors, the voltage V_{sm} and the current I_{sm} have their upper and lower limits [7].

For the SMES unit modeled, the limits for V_{sm} are:

$$-0.438 \text{ p.u.} \leqslant V_{sm} \leqslant 0.438 \text{ p.u.}$$

Therefore, at any instant, the power P_{sm} has the following limits:

$$-0.1314\ I_{sm0}\ \text{p.u.} \leqslant P_{sm} \leqslant 0.6044\ I_{sm0}\ \text{p.u.}$$

In order to control the power balance of the synchronous generator effectively during the dynamic period, the SMES unit is located at the generator bus.

3. SMES control strategy

Fig. 2 shows the proposed SMES controller for simultaneous control of P–Q compensation of the SMES unit. The control strategy uses two different controllers; a PI controller, which generates active power compensation and a voltage controller, which generates reactive power compensation. The active power compensation P_{sm} is used to stabilize the P–f loop, and the reactive power compensation is utilized to stabilize the Q–V loop.

3.1. The design of the PI controller

The control signal U_{sm} of Fig. 2 can be obtained as

$$U_{sm} = \frac{sT_w}{1 + sT_w}\left(K_P + \frac{K_I}{s}\right)\Delta\omega \tag{11}$$

where T_w is the washout time constant and K_P and K_I are the gains of the PI controller. These gains are determined by using the pole assignment technique [7,8] and are found as

$$K_P = 45.99$$

$$K_I = 376.4$$

In determining K_P and K_I, prespecified eigenvalues are chosen according to the degree of damping expected from the generator. If the parameter values of the PI controller are out of the suitable range, the assisted eigenvalues must be adjusted until the parameters values fall within the acceptable range.

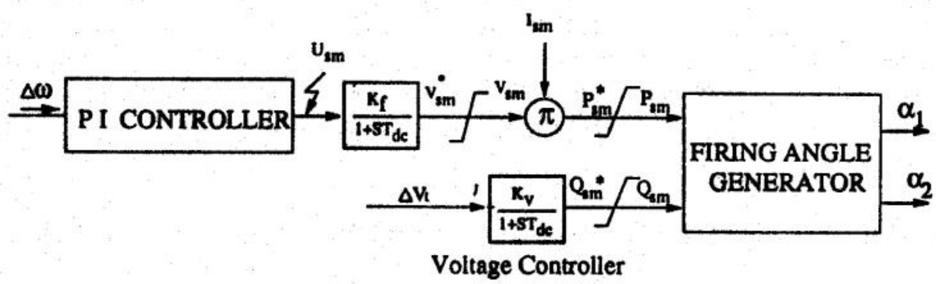

Fig. 2. SMES control strategy.

The SMES voltage can be obtained from U_{sm} by using the following relationship

$$V^{*}_{sm} = \frac{K_f}{1 + sT_{dc}} U_{sm} \tag{12}$$

where V^{*}_{sm} is the actual SMES voltage. Once V_{sm} is fixed, the active power compensation provided by the SMES unit can be determined as

$$P^{*}_{sm} = V_{sm} I_{sm} \tag{13}$$

where I_{sm} is the sensed inductor current.

3.2. The design of the voltage controller

The addition of the voltage controller enables the SMES unit to operate under four quadrant modes. Independent controls of P and Q are possible under these modes of operation. The determination of reactive power compensation is given below.

Let ΔV_t be the voltage deviation at the terminal bus of the generator because of a sudden change in load. Then, the desired Q-modulation of the SMES unit can be derived as

$$Q^{*}_{sm} = \frac{K_v}{1 + sT_{dc}} \Delta V_t \tag{14}$$

where K_v is the amplifier gain and T_{dc} is the delay time of the converter. The gain K_v is determined by simulating a very large disturbance, which gives the maximum deviation in the busbar voltages during the post fault condition. Knowing this maximum deviation value and the possible maximum Q_{sm} to be provided by the SMES unit, the value of K_v is found in this study as 2.7.

Under the equal-α mode $[\alpha_1 = \alpha_2 = \alpha]$ of control, the active and reactive powers to be consumed by the SMES unit are given by

$$P_{sm} = 2V_{sm0} I_{sm} \cos \alpha \tag{15}$$

$$Q_{sm} = 2V_{sm0} I_{sm} \sin \alpha. \tag{16}$$

As described earlier, the active power P_{sm} has its own upper and lower limits. The same is true for the reactive power Q_{sm}. Therefore, the value of P_{sm} and Q_{sm} may or may not be equal to the desired P^{*}_{sm} and Q^{*}_{sm}. For a particular value of inductor current, the maximum MVA will be provided by the SMES unit under the equal-α mode. If the variation of the inductor current is small, for large values of SMES inductance, one can write

$$2V_{sm0} I_{sm} = 2V_{sm0} I_{sm0} = S_{max} \tag{17}$$

where S_{max} is the maximum MVA available in the SMES unit. When operated under equal-α mode,

$$P_{sm} = S_{max} \cos \alpha \text{ and } Q_{sm} = S_{max} \sin \alpha.$$

Under unequal α-mode of control [2],

$$P_{sm} = S_{max}\,(\cos\alpha_1 + \cos\alpha_2)/2$$

$$Q_{sm} = S_{max}\,(\sin\alpha_1 + \sin\alpha_2)/2.$$

Defining $S^* = \sqrt{(P^{*2}_{sm} + Q^{*2}_{sm})}$,

If $S^* < S_{max}$, then $P_{sm} = P^*_{sm}$ and $Q_{sm} = Q^*_{sm}$

If $S^* > S_{max}$ then $P_{sm} = P^*_{sm}$,

and the magnitude of Q_{sm} can be calculated as

$$Q_{sm} = \sqrt{(S^2 - P^{*2}_{sm})}$$

and this is always less than Q^*_{sm}. However, the sign of Q_{sm} should be the same as that of Q^*_{sm}.

Knowing P_{sm}, Q_{sm} and the present value of the inductor current I_{sm}, the firing angles of the converter under four-quadrant operation can be calculated as shown in Ref. [2] as

$$\alpha_1 = \cos^{-1}(P_{sm}/S) + \cos^{-1}(S/S_{max}) \tag{18}$$

$$\alpha_2 = \cos^{-1}(P_{sm}/S) - \cos^{-1}(S/S_{max}). \tag{19}$$

4. The multi-machine system

A system with two machines connected to an infinite bus is shown in Fig. 3. Two SMES units of the same rating are connected to the generator terminals. The system has the following parameters (all values are in p.u. unless specified otherwise):

Network: line 1–2 $R = 0.018$, $X = 0.11$, $B = 0.226$; each line 2–3 $R = 0.008$, $X = 0.05$, $B = 0.098$; line 1–3 $R = 0.007$, $X = 0.004$, $B = 0.082$; $Y_{L1} = 0.3–j0.15$; $Y_{L2} = 0.4–j0.2$.

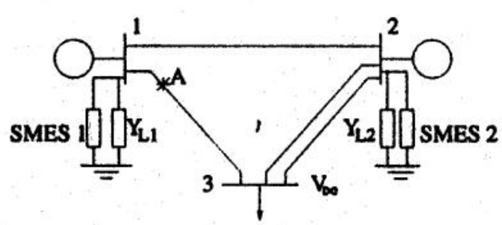

Fig. 3. Two machine–three bus system.

Mechanical Power:	$P_{m1}=1.2$, $P_{m2}=1.0$.
Generator:	160 MVA, 15 kV, 0.85 p.f., $M_g=4.74$ s, $X'_d=0.245$ p.u., $R_a=0.001096$, $D_g=0$, $X_d=1.70$, $X_q=1.64$, $T'_{q0}=0.075$ s, $T'_{d0}=5.9$ s, $P_{m0}=1.0$, $V_{t1}=1.04$, $V_{t2}=1.02$.
Voltage regulator:	$K_A=400$, $T_A=0.05$ s, $K_F=0.025$ s, $T_F=1.0$ s, $\lvert E_{FD}\rvert \leq 7.5$.
Network:	$R_e=0.01$, $X_e=0.4$.
SMES Unit:	$I_{sm0}=0.6495$, $V_{sm0}=0$, $L_{sm}=0.5$ H, $W_{sm0}=4.0$ MJ, $T_{dc}=0.026$ s.
PI Controller:	$K_P=45.99$, $K_I=376.4$.

The multimachine system is described by the following differential and algebraic equations:

$$\dot{\delta} = \omega_i - \omega_{\text{ref}} \tag{20}$$

$$\dot{\omega}_i = (-D_i \cdot (\omega_i - \omega_{\text{ref}}) + P_{mi} - P_{Gi} - P_{smi})/M_i \tag{21}$$

$$\dot{E}'_{qi} = (-E_{qi} - (X_{di} - X'_{di}) \cdot I_{di} + E_{fdi})/T_{d0i} \tag{22}$$

$$\dot{E}'_{fd} = (-E_{fd} + K_a(V_{\text{ref}} + V_s - V_t))/T_a \tag{23}$$

$$P_{Gi} = V_{di}I_{di} + V_{qi}I_{qi} \tag{24}$$

$$Q_{Gi} = V_{qi}I_{di} - V_{di}I_{qi} \tag{25}$$

$$I_{di} = (E'_{qi} - V_{qi})/X'_{di}) \tag{26}$$

$$I_{qi} = -(E'_{di} - V_{di})/X'_{qi}) \tag{27}$$

$$V_{di} = V_i \sin(\delta_i - \alpha_i) \tag{28}$$

$$V_{qi} = V_i \cos(\delta_i - \alpha_1) \tag{29}$$

$$P_{Gi} - P_{Li} = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\alpha_i - \alpha_j - \gamma_{ij}) \tag{30}$$

$$Q_{Gi} - Q_{Li} = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\alpha_i - \alpha_j - \gamma_{ij}). \tag{31}$$

For a multimachine system, we must obtain the relationship between the d–q axis currents and voltages. First, the various branch quantities have to be expressed to the same reference frame.

Then, all machine coordinates must be converted to the system reference and, finally, obtain a relationship between the currents and voltages. The procedure is given in Ref. [10]. The system dynamics are obtained by solving the above differential and nonlinear equations in a MATLAB environment. To show the effect of SMES in the multi-machine system, one scenario is presented here:

The system shown in Fig. 3 is subjected to a symmetrical three-phase fault at point A, situated 15% from the generator end of the line 1–3. The line is returned to service with a fault clearing time $t_c = 0.13$ s. The response of the important system states with and without the SMES units are shown in Figs. 4 and 5. The SMES voltage and the active and reactive power variations are shown in Fig. 6.

5. Performance analysis

Since the fault is near machine 1, it causes large fluctuations in the rotor angle and speed and the terminal voltage of machine 1 as expected. Because of the interaction, machine 2 is also affected. Unlike machine 1, the rotor speed oscillations of machine 2 show a marked unidirectional shift. During the fault period of 0.13 s, the transfer of energy from the machines to the infinite busbars is considerably reduced, and hence, the input mechanical energy during this period appears as an increase in the kinetic energy of the system. Since the line resistances are inherently low, oscillations persist for a long time. In the present analysis, the rotor speeds settle down to their steady values only after 18 s. In the absence of the SMES units, both busbar voltages V_{t1} and V_{t2} also oscillate for a long time. The application of the SMES units not only reduces the settling time but also reduces the fluctuation in the speeds of the

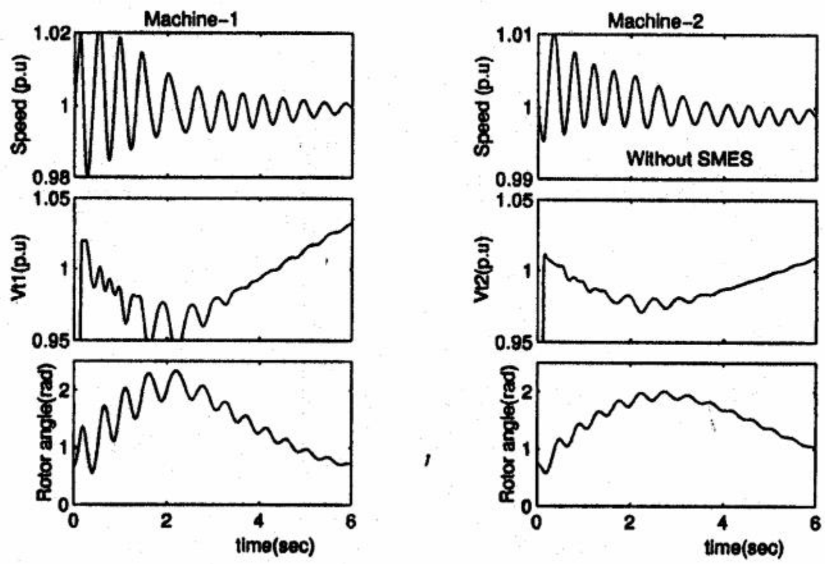

Fig. 4. System performances without SMES.

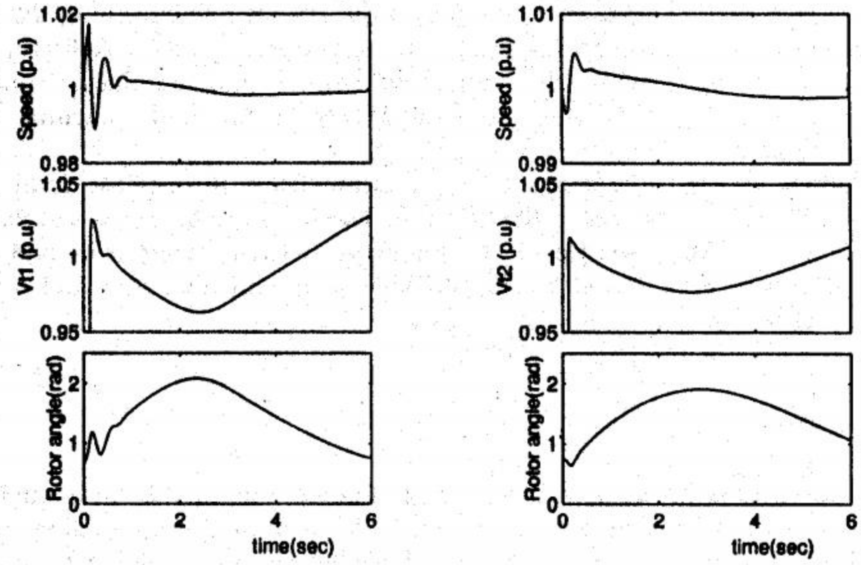

Fig. 5. System performances with SMES.

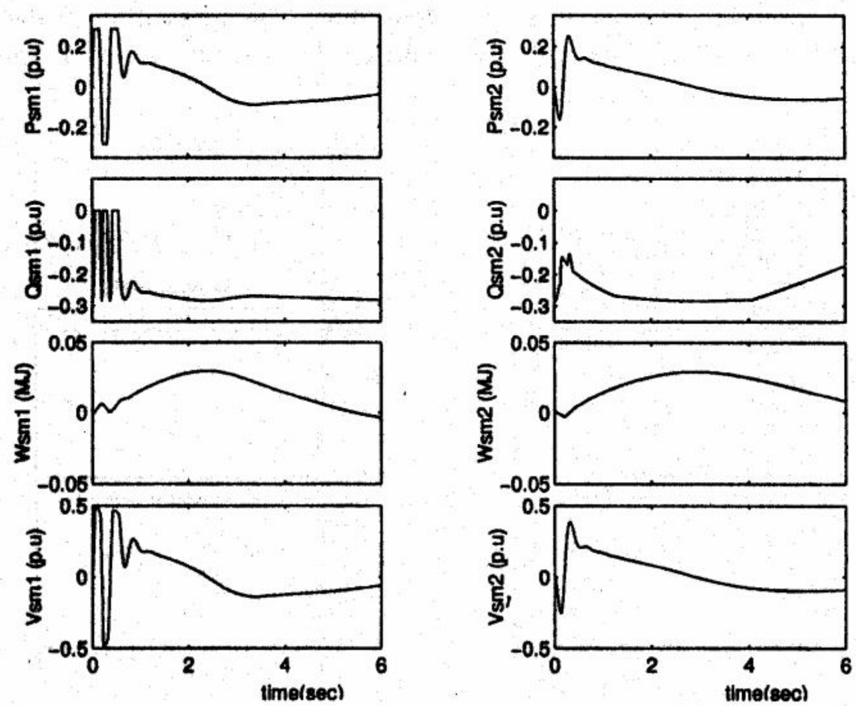

Fig. 6. SMES voltage, active and reactive power compensations.

generators, busbar voltages and rotor angles. The SMES unit acts as an efficient damper, absorbing surplus energy from the system and releasing energy when required. As can be seen from the transient response, the efficacy of the SMES unit in damping the superimposed high frequency oscillations is directly proportional to the magnitude of the overshoot. This effect is clearly visible in Fig. 5, where, for machine 1, a small amount of oscillations still persists during the immediate post-fault period. For machine 2, there are hardly any oscillations. In the present analysis, the settling time for the rotor speeds is about 7 seconds when SMES units are used for power compensation. Several other disturbances, such as a sudden change in network configuration and load rejection, were also simulated, and their results analyzed. All such disturbances create a 'quantum' of energy surplus (or deficit). If left unchecked, this gives rise to unwarranted oscillations which may increase in time, causing major faults, such as turbine shaft failure or system separation [2]. All the results obtained show that the SMES unit is well suited for suppressing such oscillations, since it is capable of absorbing the surplus or releasing the deficit energy at the appropriate time.

6. Conclusion

In this paper, the application of SMES units in a multi-machine system has been studied. Both active and reactive power compensations have been used to improve the performances of the P–f and Q–V loops. By using two controllers, the firing angles of the two six pulse converters are adjusted independently. Thus, the SMES unit is capable of operating in all four-quadrant modes. As a result, a SMES unit of relatively small rating, controlled as suggested, can effectively act as a buffer between the large power system and the disturbances that arise in the system.

In actual implementation, the control strategy proposed for the SMES unit requires primarily the measurement of speed and busbar voltage deviations. The proposed control strategy is simple and would require very little hardware to implement.

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